Restore-L Intern Final Report

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1 Restore-L Mission

Every year, approximately 20 satellites are retired because their propellants are exhausted [1]. Primarily limited by fuel, the satellites are usually fully functioning otherwise. The lifetimes of satellites can be extended with the capability of refueling. Not only would refueling extend satellite lifetime, it would also provide future satellites flexibility to prioritize other elements of their missions.

Restore-L is a Goddard Space Flight Center Satellite Servicing Projects Division mission with the primary objectives of developing tools, technologies, and techniques to extend the lifetime of satellites - even if they were not designed to be serviced in orbit. Equipped with five key servicing technology elements, the Restore-L Servicing Vehicle will demonstrate industry-changing satellite servicing technologies. The primary goal of the Restore-L mission is to rendezvous with, grasp, refuel, and relocate a government-owned satellite to extend its lifetime. The Propellant Transfer Subsystem (PTS) is required to deliver measured amounts of fuel to the client satellite in a safe manner.

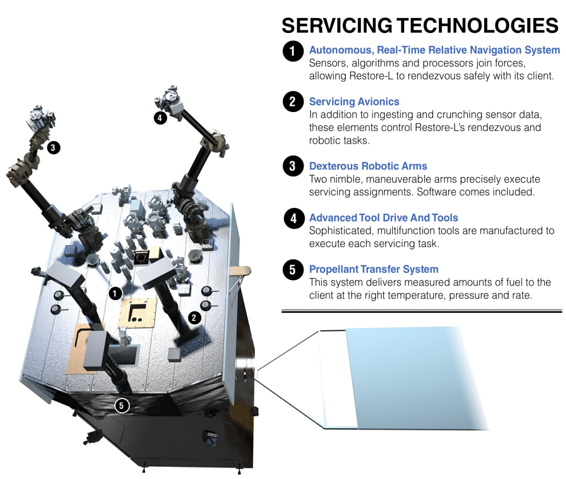

Figure 1: Servicing Technology Elements [2]

2 Water Hammer

Water Hammer is a surge in pressure that occurs when a fluid is forced to suddenly change velocity. This phenomena occurs during priming - when the lines are initially being filled with propellant. If sufficiently large, the pressure surge could cause damage to components in the Restore-L or client spacecraft.

Pressure surges occur in the Restore-L Propellant Transfer Subsystem when the latch valve downstream of the Restore-L propellant tank is opened for priming. It is mission critical to sufficiently mitigate the effects of water hammer such that components of the Restore-L and client spacecrafts are not damaged. Water Hammer may be estimated using the Joukowsky equation shown in Equation 1, where ρ is the liquid density, u_f is the change in liquid velocity, and c is the compersssional wave speed.

$$\Delta P_{WH} = \rho u_f c \tag{1}$$

3 Testing

To characterize the expected pressure surge, empirical testing of water hammer is performed on a system representative of the Propellant Transfer Subsystem. For safety reasons, deionized water is used in substitution of the toxic Hydrazine monopropellant. A pressure scaling law is used to scale the measured pressure surges of water to hydrazine. Several Pressure transducers are used to measure pressure along the propellant lines. High speed pressure transducers are used to ensure data capture of the pressure surge peaks. Multiple trials of different configurations are run where hardware such as filters and orifices is changed. Additionally, different staging procedures are tested to determine the best propellant priming operation.

4 Analysis & Results

The pressure scaling law shown in Equation 2 is used to scale the measured pressure from water to Hydrazine [2]. The speed of sound in the fluid, c is found using Equation 3, where E is the elastic modulus, D is the pipe inner diameter, t_w is the tube wall thickness, and μ is Poisson's ratio. It is found that the pressure surge in Hydrazine is expected to be 30% higher than that of water.

$$\frac{(P_{surge})_{N_2H_4}}{(P_{surge})_{H_2O}} = \frac{(c\sqrt{\rho})_{N_2H_4}}{(c\sqrt{\rho})_{H_2O}} \tag{2}$$

$$c = \frac{c_0}{\sqrt{1 + \frac{\rho c_0^2}{E}\left(\frac{D}{t_w}\right)(5 - 4\mu)}} \tag{3}$$

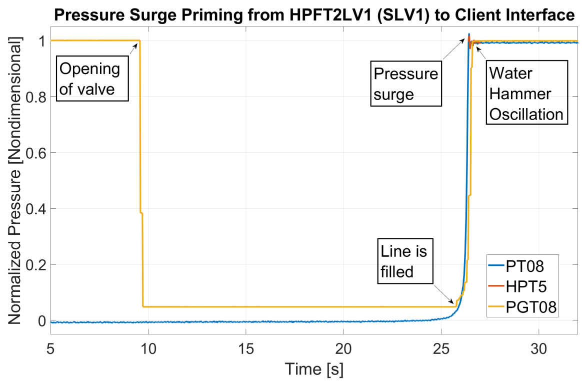

Figure 2: Sample Water Hammer from Priming

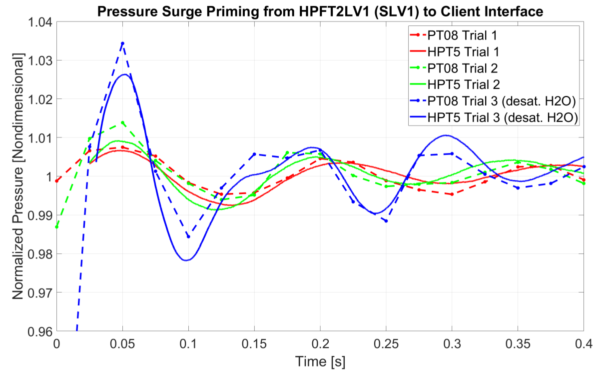

Figure 3: Sample Water Hammer Oscillation

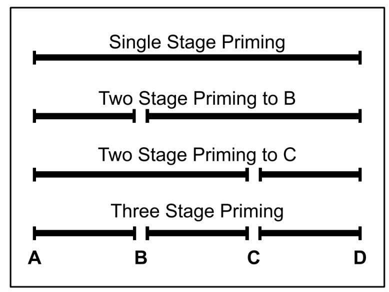

Figure 4: Priming Configurations

When an orifice or cavitating venturi is used and the valve is initially opened a sudden drop in pressure is measured, as shown by PGT08 in Figure 2. The pressure remains at that level until the line fills and there is a spike in pressure that eventually equilibrates to the tank pressure. The pressure transducer at the end of the line, PT08, also measures a spike in pressure. However, the pressure surge may occur in such a short amount of time that its peak value is not captured by the relatively low sampling rates of the PT08 and PGT08 sensors. A high-speed pressure transducer, HPT5, is used at the end of the line to measure the true peak value of the pressure surge.

For the shown configuration of priming from SLV1 to the Client Interface, the pressure surge occurs over a duration long enough such that the low-speed pressure transducers are able to capture the peak. This is confirmed by the high-speed and low-speed pressure transducers giving similar results. The pressure oscillation that occurs due to the pressure wave sloshing between the ends of the pipe can be observed in Figure 3. Note that Trial 1 and 2 are very close in wave amplitude and frequency. Trial 3 is run with H2O desaturated of dissolved Helium; it is hypothesized that saturated water dampens the pressure wave. Thus, a higher pressure peak is observed in Trial 3.

Tests are currently being run to determine the best priming configuration. There are four possible operations as shown in Figure 4. The best priming operation will be determined based on the peak pressures observed in the tests and the components at the ends of each line.

5 Future Work

The Restore-L spacecraft is scheduled for launch in late 2023. The PTS passed a subsystem CDR in mid-July of 2019. Future work will include further testing and analysis of the PTS. Based on the results, modifications may be made to the system design or priming operation to reduce pressure surge.

References

[1] NASA Goddard Space Flight Center, “On-Orbit Satellite Servicing Study Project Report,” NP-2010-08-162-GSFC, October 2010

[2] NASA, “Restore-L - Proving Satellite Servicing,” NP-2016-2-392-GSFC, September 2017

[3] Harbaugh, J., “Satellite Servicing TDM Project Overview,” *NASA* Available: https://www.nasa.gov/mission_pages/tdm/satellite-servicing.html.

[4] Kandula, Nufer, ”RESTORE-L-EM-002025PTS Pressure Surge,” RESTORE-L-EM-002025PTS, August 2016